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Permalink

<https://escholarship.org/uc/item/3464b75v>

ISBN

9780780390034

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Publication Date

2005-12-01

DOI

10.1109/ICORR.2005.1501046

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Learning to Perform a Novel Movement Pattern using Haptic Guidance: Slow Learning, Rapid Forgetting, and Attractor Paths

J. Liu, J.L. Emken, S.C. Cramer, D.J Reinkensmeyer, *Member, IEEE*

Abstract— Mechanical guidance is a common technique to teach patients desired movement patterns during motor rehabilitation, but little is known about the motor learning processes involved with this technique. In this study we examined how well unimpaired subjects could learn to trace a novel path after they practiced it with mechanical guidance from a robot. The form of haptic guidance used was a virtual channel that constrained the hand to follow the desired path (a snake-like curve). Subjects substantially improved their ability to trace the path following practice with haptic guidance, relative to their performance following an initial visual demonstration. They slowly improved their performance with more haptic training. However, when asked to reproduce the path repeatedly, their performance degraded over the course of a few trials. The tracing errors were not random, but instead were consistent with a systematic evolution toward another path, as if being drawn to an “attractor path”. These results suggest that haptic demonstration can improve short-term performance of a novel desired trajectory. However, in the short term, the motor system is inclined to repeat its mistakes following just a few movements without guidance.

Keywords— arm, movement, motor control, adaptation

I. INTRODUCTION

Robotic devices are increasingly being used as tools for movement training following neurologic injury [1-3]. They are also candidates as tools for training skillful movements, such as those required for surgery or athletics. The predominate training paradigm that has been explored so far in rehabilitation is mechanical guidance; that is, the robotic device physically guides the patient’s limbs through a desired trajectory. Mechanical guidance can improve motor recovery of the arm following stroke, and of gait following stroke and spinal cord injury [4-8]. However, it is still unclear what the advantages of mechanical guidance are compared to other movement training techniques, including unassisted practice [6], error-amplification techniques [9, 10] and visual demonstration [11].

One way that mechanical guidance might be beneficial is in demonstrating a novel, complex desired trajectory.

This work supported by a U.C. Irvine Multi-Investigator Faculty Research Grant.

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For example, a common problem addressed by therapists during rehabilitation of arm movement after stroke is that patients perform arm movements with abnormal kinematics. Patients use the redundant degrees of freedom of their arm and torso in patterns that therapists consider to be incorrect. Use of incorrect patterns is thought to lead to repetitive use injuries. Use of incorrect patterns may also limit the ability of the patients to achieve higher levels of movement ability by acting as a sort of “local minimum” during recovery.

A common technique to address the problem of incorrect movement patterns is to demonstrate the correct movement trajectory by manually moving the patient’s limb through it. The premise is that subjects will gain insight into how to replicate the desired trajectory by experiencing it. It is currently unknown how effective this technique is. The goal of this study was to identify how well unimpaired subjects could improve their ability to perform a novel movement pattern with guidance provided by a robot.

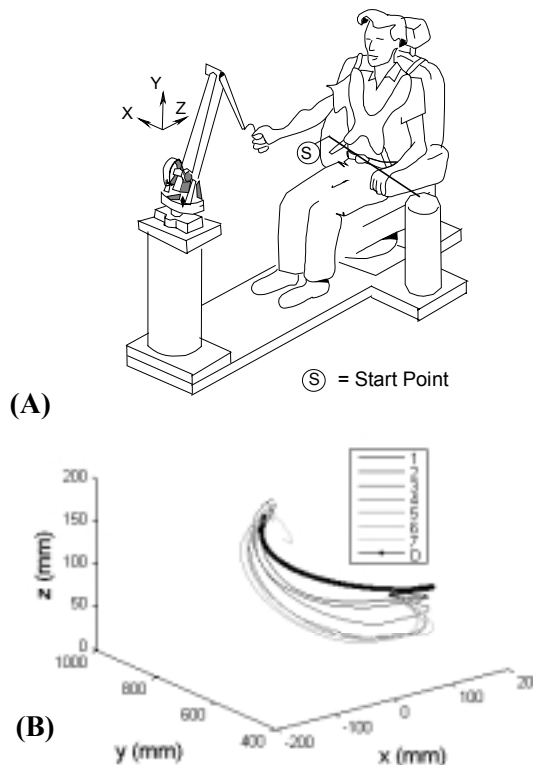


Figure 1: (A) Experimental set up. The subject held the tip of a lightweight robot and tried to move from a start position (S) along a desired novel path. (B) Example 3-D view of the tip of the robot during a test cycle. The dark line is the desired path (D), and the lighter lines show seven consecutive attempts to reproduce that path.

II. METHODOLOGY

A. Experimental Protocol

Four healthy adult subjects learned to make a novel 3-D path (Figure 1). Both the right and left hand were tested for each subject. Subjects held a lightweight haptic robot (PHANTOM 3.0, SensAble Technologies, Inc.). The robot measured the motion of the hand at 200 Hz, and provided haptic guidance in some conditions (Figure 1).

The novel 3-D paths were curves on the surface of a sphere. In spherical coordinates, the equation of a sphere is:

$$\begin{cases} x = \rho \cdot \cos \theta \cdot \cos \phi + x_0 \\ y = \rho \cdot \sin \theta \cdot \cos \phi + y_0 \\ z = \rho \cdot \sin \phi + z_0 \end{cases} \quad (1)$$

where $[x_0 \ y_0 \ z_0]$ is the center of the sphere, ρ is the radius, and θ and ϕ are pitch and yaw angles. We set θ and ϕ to be linearly related to generate a curve on the sphere:

$$\phi = c_1 \cdot \theta + c_2$$

where c_1 and c_2 are constants. We varied c_1 , c_2 and the range of θ to generate novel paths. Each subject experienced a different path for each hand. A typical path is shown in Fig. 1.

The experimental protocol consisted of an initial visual demonstration of the desired path, followed by haptic training. For the initial visual demonstration, the tip of the robot arm was programmed to move along the desired path. The robot was controlled with a position feedback controller, and the movement duration was set to be 4 seconds. During this visual demonstration, subjects watched the robot move along the desired path, with their hands resting in their laps. The robot repeated the desired movement seven times. The subject was then asked to reproduce the desired path seven times with the robot passive (i.e. in a “null field”). The starting location for the desired path was marked with a small pointer. The subjects heard a computerized “beep” when they moved the robot tip to the starting location, and another “beep” if they successfully moved the tip to within 3 cm of the endpoint of the desired path. If they did not reach the endpoint accurately, the ending beep was sounded after 4 seconds.

Following the initial visual demonstration, subjects experienced two alternating haptic training protocols, which were repeated a total of 9 times (or 9 “cycles”): the continuous channel condition and the alternating channel condition. In the continuous channel condition, a virtual channel was presented 7 times in a row (CCCCCCC). The channel shape matched the shape of the desired path; thus, subjects were constrained to move along the desired path, although they controlled the progress along that path. The wall stiffness of the virtual channel was 5 N/mm. In the alternating channel condition, the channel was alternated with a null field (CNCNCNC). Subjects were able to view their hand movements during haptic training.

Following the 7 movements in each training condition, a testing cycle was presented. For this cycle, the subject was asked to reproduce the desired path 7 times in a null field. The subject was verbally informed of their tracing error after each test. Subjects rested with the hand on the lap for approximately 10 seconds after each testing cycle to avoid fatigue.

The continuous channel and alternating channel training conditions were alternated a total of 9 times each, with a testing cycle after each condition. Thus, the entire protocol can be summarized as:

VVVVVVVV-NNNNNNNN-(rest)-{CCCCCCC-NNNNNNNN-(rest)-CNCNCNC-NNNNNNNN-(rest)}

where V = visual demonstration, N = subject tries to reproduce path in null field, C = channel, and the {bracketed protocol} is defined as a “cycle”, which was repeated a total of nine times

B. Data Analysis

The robot control loop executed at 1000 Hz, and the position of the robot tip was stored at 200 Hz. We defined the “tracing error” as the mean distance between each recorded point and the closest point on the desired trajectory.

We used repeated measures ANOVA to test for an effect of three factors on tracing error. The three factors were: test cycle number, reach number in each test cycle, and training condition. Each of these factors was considered a within-subject measure for a repeated measures ANOVA using SPSS software.

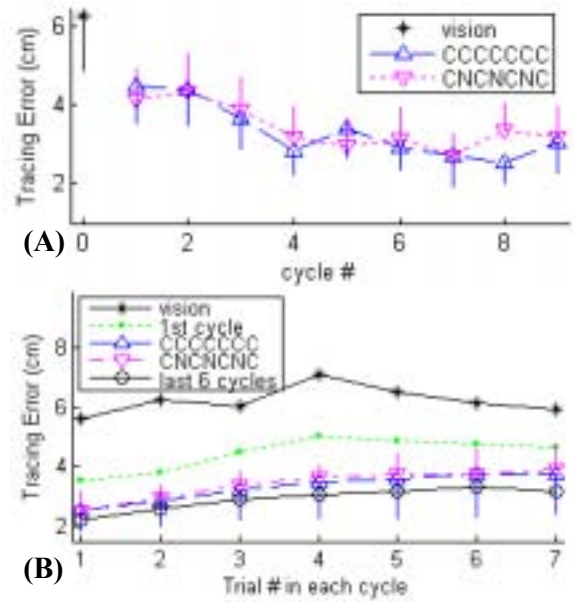


Figure 2: (A) Improvement in tracing error across training cycles. (B) Forgetting process in test section of each cycle. The error bars show one standard deviation across arms tested.

III. RESULTS

A. Path tracing accuracy improved following haptic guidance

The subjects improved their ability to reproduce the novel path by experiencing it haptically. Figure 2 shows the tracing error, averaged across testing cycles. Haptically experiencing the trajectory with vision of arm for just one training cycle significantly reduced the tracing error compared to the tracing error following visual demonstration ($p < 0.0001$). The tracing performance continued to decrease across the 9 training cycles. The repeated measures ANOVA indicated that there was a significant linear contrast ($p = .03$) of cycle number on

tracing error. There was no significant effect of training technique (i.e. alternating versus continuous channel) on tracing error.

B. Path tracing error quickly increased when guidance was withheld

Figure 2b shows the tracing error as a function of the reach number during the test cycle. There was a significant increase in tracing error as the subjects attempted to reproduce the path repeatedly during the testing phase of each cycle ($p < .001$). This “forgetting” occurred rapidly -- over the 7 tracing attempts in the testing phase of each cycle.

C. Tracing error was consistent with a systematic evolution toward an “attractor path”

Visual inspection of the hand paths during the testing phase of each cycle suggested that the increase in trajectory error was due to a systematic and progressive distortion in the hand path, rather than to a random pattern of tracing errors (e.g. Figure 1b). Therefore, we hypothesized that the motor system is configured in such a way as to contain “attractor paths” toward which the subjects hand paths evolved in the absence of haptic guidance.

To test this hypothesis, we first compared the tracing error when the desired path was used as the reference, to the case where the last reach (reach 7) of the testing phase was used as the reference. If the hand path evolved systematically toward an attractor path during “forgetting” then the former should have increased systematically (as the hand path evolved away from the desired path) and the latter decreased systematically (as the hand path was drawn toward the attractor path). Figure 3A shows that this was the case. The tracing error relative to the demo path increased significantly with each reach during testing ($p < 0.001$), while the error relative to the last reach in the test phase decreased significantly ($p < 0.001$).

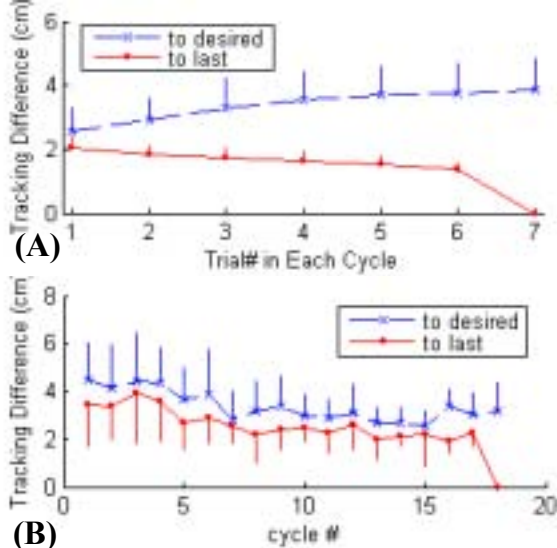


Figure 3: (A) Mean tracing error within the test cycles, calculated with respect to two different reference paths: the desired path, and the last path of the test cycle. (B) Mean tracing error across test cycles, calculated with respect to two different reference paths: the desired path, and the last reach of the last testing cycle. The error bars show one standard deviation across arms tested.

We then sought to determine to whether the putative attractor path was the same across the 18 total testing cycles (i.e. the 9 testing cycles after the alternating channel protocol, and the 9 testing cycles after the continuous channel protocol). We quantified the tracing error for the last reach (i.e. the 7th reach) in each testing cycle in two conditions: when the desired path was used as the reference, and when the tracing error for the last reach in the last cycle (i.e. the 18th cycle) was used as the reference. If the attractor path remained constant across cycles, then the error with respect to the desired path should be consistently greater than the error with respect to the very last reach in the last cycle. This was the case (Fig. 3, $p < 0.0001$). This supports the idea of a fairly consistent “attractor path” during forgetting. However, the attractor path was not completely static. The last hand path in each testing cycle slowly evolved to be closer to the desired path, as well as to be closer the very last reach of the last cycle (Fig. 3B, $p < 0.001$). These findings are consistent with the idea that the attractor path slowly evolved toward the desired path over the course of the 18 testing cycles.

IV. DISCUSSION

Haptic guidance substantially improved the subject’s ability to trace the desired path, compared to performance after an initial visual demonstration of the desired path. Subsequent training with haptic guidance slowly improved tracing ability even more. These results support the use of haptic guidance, and more specifically, the use of a virtual channel that constrains arm movement but does not propel it, as a technique for teaching people to move along novel paths. Haptic guidance in which the robot propels the arm through a path has also been shown previously to be effective in path learning [11].

Future work will test impaired subjects. The presence of motor or perceptual impairments will likely decrease the efficacy of haptic guidance, because such impairments will make it difficult to perceive or implement the desired path. However, our results indicate that the motor system is normally capable of interpreting haptic guidance in order to improve motor performance; thus, there will likely be at least some residual ability to learn from haptic guidance following neurologic injury.

A difference between the protocol examined here and the normal clinical situation is that we guided only the hand of the subject, while therapists typically guide the whole arm. Guiding the whole arm may help subjects to better learn the desired movement because it makes it unnecessary for them to select the redundant elbow, shoulder, and wrist joint angles that determine hand position.

Haptic guidance substantially decreased error compared to performance after visual tracing. This decrease was followed by a slower decrease in error with hundreds of guided trials. One implication of this finding is that haptic guidance may have a large short-term effect on motor performance, followed by a slower learning process. In a clinical setting, then, a few hands-on demonstrations may make a considerable, rapid difference to a patient, while further sustained improvements might depend on hundreds of guided practice trials.

A key finding was that the tracing error rapidly increased over the course of several trials when haptic guidance was withheld. The phase of training did not reduce the amount of forgetting: forgetting occurred both early and late in training, although the starting error from which forgetting commenced was smaller later in training (Figure 3). This suggests that forgetting is a persistent issue even with substantial training.

Another interesting finding was that the increase in tracing error was not random, but instead was consistent with a systematic evolution toward another path. Systematic distortions in the haptic perception of geometry have been observed previously, with subjects “regularizing” shapes to make them more symmetrical [12]. We speculate that the motor system is configured in such a way to contain “attractor paths”. These paths may arise because they correspond to commonly perceived shapes. Alternately, they may minimize effort or perhaps smoothness, or perhaps they are a basis set for constructing arbitrary paths. The results of this study suggest that attractor paths can be altered with training, as the hand path on the last reach in each test cycle got systematically closer to the desired path with training (Fig. 1B). Thus, one benefit of haptic path training may be to produce a slow, permanent improvement in the attractor path.

One practical implication of the finding of rapid forgetting is that much of the immediate effect of manual guidance may be lost with further, unguided practice, due to an evolution toward “default modes of moving” (i.e. attractor paths). Devising strategies to reduce forgetting and alter attractor paths is an important goal for future research.

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